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The Combined Effects of River Flow and Water Quality on Freshwater Fish Population Dynamics

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Abstract. The aquatic ecosystems of the rivers maintain aquatic biodiversity, and freshwater fish are important bioindicators for the ecological health of a river. Compound stress on fish populations all over the world has been caused by hydrological changes and water quality degradation due to intensive human activities such as dam regulation and pollutant discharge. This study focused on the lower reaches of the Yellow River, and investigated the independent and interactive impacts of river flow and water quality on the dynamics of freshwater fish populations based on multiple-year field monitoring data from 2014 to 2023. Flow variation accounted for 21% of the temporal variation in fish community and was found to have a significant influence on fish spawning cues, habitat availability, and physiological metabolism of the fish, while water quality accounted for 15% of the temporal variation in fish community and was the most limiting factor in the most heavily polluted river reach. Low flow conditions increased risk of pollutant accumulation, flood conditions increased both pollutant accumulations and introduced non-point source pollution risks; there were non-additive coupled interactions between flow and water quality. Benthic resident fish had higher tolerance to composite stress while pelagic and migratory fish had higher sensitivity to hydrological/water quality co-stress. Single factor regulation would hardly be enough to restore fish communities, coordinated regulation of flow regime and water environment was needed. This paper offers scientific evidence for watershed ecological controls and fish biodiversity conservation under various human disturbances.

Keywords: River flow, water quality, fish population dynamics, fresh water biodiversity

1. Introduction

Fluvial freshwater ecosystems sustain global aquatic biodiversity and underpin watershed ecological stability, with freshwater fish functioning as critical indicator taxa and key constituents of aquatic food webs [1]. Over the last decades, intensified human alterations of river systems have greatly affected natural ecological conditions throughout the world. The natural hydrological rhythm is disrupted by the widespread construction of hydraulic engineering facilities, and the processes of natural sediment transport are broken, whilst intensive agriculture and industrial emissions and discharge of domestic sewage from cities are continuously degrading the water environment of rivers. The inherent dynamic equilibrium between river hydrology and water quality is constantly disrupted by man-made activities, thus exposing the freshwater fish communities to a chronic

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double stress due to alteration of the hydrological regime and water environment. Such composite disturbances have triggered widespread population decline and biodiversity reduction of freshwater fish, severely undermining the structural and functional integrity of river ecosystems.

Global scholars have carried out extensive explorations on the ecological responses of fish populations to hydrological variation and water quality change and formed relatively mature theoretical and methodological systems. Research on ecological flow has evolved from basic hydrological statistical evaluation and habitat simulation to comprehensive multi-dimensional assessment of hydrological regime integrity, fully confirming the decisive role of natural flow characteristics in fish survival and reproduction [2]. Water quality-oriented studies have clarified interspecific differences in fish tolerance to key environmental factors such as dissolved oxygen, water temperature and nutrient enrichment. Existing research has gradually shifted focus to multi-stressor interactive effects under climate change backgrounds, though most studies still rely on two-factor combination analysis while systematic research on complex multi-factor coupling mechanisms remains scarce [2, 3].

Domestic research concentrates on typical major river basins and has yielded substantial practical findings. Previous studies have clarified dominant pollution indicators affecting local fish communities, calibrated key environmental thresholds for regional water ecological management and verified the seasonal variability of ecological water demand for native dominant fish species. Laboratory simulation experiments have further defined fish behavioral and physiological responses to different flow velocity conditions and preliminarily revealed the interactive rule of hydrological and water quality factors on aquatic organisms. Overall, domestic and foreign studies have fully verified the independent ecological effects of flow and water quality on fish populations. Few studies integrate the two core factors to analyze their coupled synergistic or antagonistic effects, and the differential response mechanisms of different fish functional groups to composite stress still lack systematic elaboration.

Against the above research gaps, this study takes the lower reaches of the Yellow River with intense human intervention as the research object. It aims to break through the limitation of traditional single-factor research and systematically clarify the independent and coupled effects of river flow and water quality on freshwater fish population dynamics. This study also explores the differentiated adaptation strategies of various fish functional groups under composite environmental stress, so as to provide a scientific basis for watershed ecological regulation and fish biodiversity protection.

This paper adopts a progressive analytical framework for systematic research. It first summarizes the basic environmental and ecological status of the study area. It then separately analyzes the independent impacts of flow fluctuation and water quality change on fish communities. On this basis, it further explores the coupling interaction mechanisms of the two environmental factors and interprets the differentiated response characteristics of diverse fish functional groups. Finally, targeted optimization strategies for water resource scheduling, water quality management and fish ecological protection are proposed to support watershed ecological restoration.

2. Research materials and core analysis

2.1. Overview of the study area and data sources

The lower Yellow River is the research focus of this study. The region has high anthropogenic hydrological alteration, high water pollution pressure, which provides good opportunities to study flow and water quality coupled ecological effects. The research data are the outcome of systematic

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and large-scale field surveys that have been conducted from 2014 to 2023 targeting the hydrological environment, water quality parameters and aquatic ecosystems. Data from nine representative monitoring sections, with long-term records of multi-dimensional indicators, are included. Hydrological and water quality parameters are flow discharge, flow velocity, water temperature, dissolved oxygen, chemical oxygen demand, biochemical oxygen demand, ammonia nitrogen and total phosphorus. Biological monitoring information primarily includes information on the abundance, distribution and composition of fish communities.

The lower Yellow River presents obvious interannual and seasonal heterogeneity in runoff distribution, with reservoir operation projects such as Xiaolangdi Reservoir profoundly reshaping natural hydrological rhythms. Water pollution problems in this region are mainly manifested by ammonia nitrogen enrichment and organic pollutant accumulation, with extreme pollutant concentrations appearing in partial river sections. Aquatic ecosystem health status shows strong spatial polarization. Partial river reaches maintain a healthy ecological grade, while heavily polluted sections fall into an extremely poor ecological grade. Local fish communities are dominated by cyprinid species, including crucian carp and common carp. Continuous field observation indicates a gradual decline of regional fish biodiversity in recent years.

2.2. The independent effect of river flow on freshwater fish populations

Flow regime acts as the core component of river hydrological environments and shapes fish habitat suitability, reproductive success and community structure through multi-scale ecological processes. Variation in water discharge directly controls wetted channel area and spatial distribution of water depth within river corridors. Sustained flow reduction shrinks shallow water habitats and narrows effective river channels, which substantially reduces available space for fish foraging, predator avoidance and overwintering. Long-term hydrological monitoring demonstrates that flow-induced hydrological changes can explain a considerable proportion of temporal variation in local fish population dynamics. For fish species with adhesive egg reproduction habits, reduced flow magnitude limits the coverage of suitable spawning substrates and weakens the population recruitment capacity of dominant native fish species [4].

Natural flow fluctuation also provides essential ecological cues to trigger fish reproductive behaviors. Major freshwater commercial fish species require rising water levels and increased flow velocity to initiate spawning activities. Hydrological stimulation during flood pulses serves as a critical natural signal for gonad maturation and oviposition. Ecological water demand during reproductive seasons presents obvious seasonal differentiation, with far higher water requirements to sustain successful fish breeding compared with non-breeding periods. Such seasonal hydrological constraints largely determine the temporal variation of fish community renewal capacity in regulated river systems.

Fish energy metabolism and physiological health status are affected in different ways by different velocity ranges. Low flows have minimal effects on fish growth and activity, and high flows will lead to greater swimming costs and metabolic load. High flow stress for an extended period retards individual growth rates and decreases the survival rate for the population. The moderate flows environment is suitable to stimulate physiological activity in fish, increase the antioxidant capacity and improve immunity. Also, moderate fluctuations in flow regimes enhance aeration efficiency and maximize dissolved oxygen regimes in water bodies, while sudden reductions in flow can induce seasonal hypoxia stress, and indirectly reduce fish habitat quality [5].

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2.3. The independent effects of water quality parameters on freshwater fish populations

The water quality conditions are limiting factors that limit the survival, growth and community succession of freshwater fish. Dissolved oxygen is the most basic environmental parameter that is essential for normal physiological activities of fish. Most fish species in surface waters are limited in their foraging, swimming, and habitation activities due to lack of dissolved oxygen. In extreme conditions, heavy oxygen depletion may result in physiological dysfunction and permanent damage to aquatic organisms, and thus in significant mortality. There are interspecific differences in the tolerance of hypoxia in fish species [6]. In general, some fish are well adaptable to low oxygen conditions (typical cyprinid fish) and others are sensitive aquatic species (sensitive fish) which need more stable and high dissolved oxygen conditions to sustain normal vital functions.

Further alteration of the spatial structure and composition of the local fish community by nutrient enrichment and organic pollution. Ammonia nitrogen is a significant toxic pollutant in the lower Yellow River, and is highly neurotoxic to fish in natural waters. The results of the field investigations indicate that there is a very strong negative correlation between ammonia nitrogen concentration and fish habitat adaptability. The continuous build-up of ammonia nitrogen significantly lowers the quality of living environments, and impedes population recovery. An excessive amounts of total nitrogen and total phosphorus promotes the advancement of eutrophication in a watershed. Intensive algal propagation also lowers water clarity and increases the oxygen consumption (in the absence of light) aggravating benthic habitat degradation and fish community stability.

The quantitative assessment of driving factors suggests that water quality variations make a moderate contribution to temporal dynamics of fish populations [1]. At the watershed scale, overall explanatory power of the water quality factors is less than that of the hydrological variables and biological interactions. In very polluted sections of the river, water quality degradation can be the limiting factor. Pollutants constantly accumulating in these regions hamper individual growth of fish, impede the reconstruction of fish communities and restrict the self-restoration capacities of aquatic ecosystems.

2.4. The composite coupling effect between water flow and water quality

Fish are not affected by hydrological regimes and water quality parameters in simple additive/indirect independent ways. Physically, chemically and biologically, the two key environmental factors interact creating unique coupled ecological effects, which in turn fundamentally determine the overall stress intensity on fish communities [7]. A primary regulatory variable for in-stream pollutant concentration, diffusion and degradation efficiency is flow variation.

In dry seasons, when runoff levels are low, capacity of water bodies to self-purify and river dilution is reduced. Stable and low flow increases hydraulic retention time allowing continuous build-up of organic pollutants, nitrogen and phosphorus nutrients. In situations where pollutant discharge intensity is stable, a decrease in water volume can have a very large impact not only on pollutant levels but also on the physiological stress of pollutant impacts on fish populations. The low-flow/high pollution combined conditions are of particular concern for sensitive fish species as they result in a significant decrease in habitat stability and an increase in extinction risks for fish communities under these conditions.Increased runoff during flood seasons presents dual environmental impacts on river water quality. Elevated flow velocity effectively dilutes point-source pollutant concentrations, enhances water aeration capacity and promotes aerobic decomposition of organic contaminants. Improved hydraulic conditions strengthen river self-purification ability and

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alleviate localized pollution stress. Nevertheless, intensive surface runoff during rainfall events carries large amounts of agricultural fertilizers, aquaculture wastewater and terrestrial pollutants into river channels. Massive input of non-point source pollutants leads to sudden water quality deterioration and forms compound pollution pressure on aquatic ecosystems [8].

Such interactive mechanisms produce ecological consequences significantly different from single-factor stress. River sections simultaneously suffering from insufficient ecological flow and excessive pollutant loading show extremely low fish population recovery potential. Regions affected by only a single environmental stress present better community stability and restoration capacity. Practical watershed management verifies that separate regulation focused merely on water quality improvement or ecological water supplementation cannot achieve effective fish community restoration. Coordinated optimization of hydrological regimes and water environmental quality is essential to mitigate composite ecological stress and maintain long-term river ecological health.

2.5. Differential responses of different fish functional groups to composite environmental stress

Combined flow and water quality stress result in very distinct responses for fish functional groups with different feeding and habitat preferences and physiological tolerances. The different adaptation characteristics among fish groups is important to understand in the context of targeted ecological protection and refined watershed management strategies. The divergence of benthic fish and pelagic fish is clearly seen in their coping strategies to the composite environmental stress. Benthic taxa like crucian carp and common carp are exposed to the river sediments during their life cycles and are more sensitive to heavy metals and POPs that are accumulated in the sediments. Benthic fish regular bioturbation under polluted conditions can indirectly affect overall habitat quality. Generally these fish groups have higher tolerance to eutrophic conditions and hypoxia, which enables them to maintain their dominant position in the very polluted sections of rivers. Pelagic fish that live in middle and upper layers of water are more sensitive to the decrease in dissolved oxygen and deterioration of water quality. In eutrophic waters, water transparency decreases and massive algal outbreaks can cause severe impacts to pelagic filter-feeding fish species.

Migratory fish and resident fish each have unique dependence on natural hydrological cycles and water conditions. Migratory fish depend on certain flow pulses and on water level changes at specific times of the year for long-distance migration and for spawning and population renewal. A change in the flow regime and reduction in hydrological periodicity may close migration pathways and interfere with the full life cycle development of migratory fish, resulting in a very rapid decline in their population numbers [9]. A moderate hydrological fluctuation has relatively wide adaptability for resident fishes. Extreme low flow events and continuous water pollution continue to result in ongoing decline in habitat and population of resident fish communities.

All of the above differential response rules fully demonstrate the need for differentiated river ecological management. Conventional unified regulation modes are not able to accommodate the different adaptive nature of different fish functional groups. Spatial variations in hydrology, levels of pollution, and fish communities should be considered when developing targeted ecological flow guarantee standards and hierarchical water quality control plans. Under the application of precision regulation, composite environmental stress to fish assemblage can be effective reduced and good technical support can be given to the conservation of biodiversity and ecological restoration of the watershed [10].

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3. Conclusion

This study examined the influence of combined action of river flow and water quality on the dynamics of freshwater fish populations using long-term monitoring data from the lower Yellow River. Results showed that both flow and water quality had both direct and non-additive interactive effects on fish communities. Flow was shown to be the major hydrological driver, accounting for 21% of the temporal variation in fish populations, which was caused by changes in habitat space and fish physiological metabolism, as well as providing spawning hydrological cues. Water quality was a 15% component of the population dynamics and became the most limiting factor in the most heavily polluted reaches of the river, where ammonia-nitrogen toxicity and eutrophication reduced fish survival and the ability of communities to recover. Pollutant stress through dilution-accumulation processes: low flow conditions during dry seasons increased the risk of pollution, and flood increased the risk of pollutant dilution as well as non-point-source pollution. Resistance to composite stress varied across fish functional groups, with benthic resident cyprinids showing high tolerance, while pelagic filter-feeding fish and migratory fish were much more sensitive to co-stress of hydrological alteration and water pollution. Coordinate joint management of flow regime and water environment is irreplaceable to restore river ecology; single-factor management cannot reverse fish community degradation. This research advances the knowledge on the multi-stressor coupling mechanisms for river fish and provides practical references for basin-scale ecological management.

However, there are still some restrictions in this study. The lack of precise quantification of the intensity of synergistic versus antagonistic interaction of flow and water quality stems from the use of field observational data, as opposed to controlled manipulative experiments. Furthermore, it is impossible to fully reflect the extent of the sampling coverage in the entire basin of the lower Yellow River, as well as the characteristics of small tributaries and their micro-habitat. It is recommended to undertake controlled experiments in mesocosms to separate the coupling intensity of multi-stressors in future studies. Future research should also include climate change scenarios to project long-term trends of variation in fish functional groups, and to optimize adaptive management of watershed regulation.

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